

## **Continued Analysis of High-Frequency Broadband Acoustic Scattering from Non-Linear Internal Waves during SW06**

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### **LONG-TERM GOALS**

To understand high-frequency broadband acoustic backscattering from small-scale physical processes, such as internal waves, turbulence, and microstructure, in shallow, stratified waters.

### **OBJECTIVES**

The primary objective of the overall research program was to measure high-frequency broadband acoustic backscattering in highly stratified, energetic environments and to determine the contribution to scattering from temperature and salinity microstructure. Testing the validity of existing scattering models and the initial development of new, and/or extensions of existing, simple physics-based scattering models was a secondary objective of this work.

To accomplish the stated objectives, high-frequency broadband (150-600 kHz) acoustic backscattering measurements were performed during the generation, propagation, and dissipation of non-linear internal waves in August 2006 as a part of the SW06/NLIWI experiment. Almost coincident microstructure measurements were collected by Jim Moum with a profiling microstructure instrument, Chameleon. The contribution to scattering from biological organisms was quantified using net-samples, from which the zooplankton taxa, size, and depth (in coarse vertical bins) can be determined.

Analysis of these data to date has focused on (1) determining the dominant scattering mechanisms giving rise to enhanced backscattering often associated with the passage of non-linear internal waves, with particular attention given to elevated scattering associated to Kelvin-Helmholtz instabilities, and (2) inverting the broadband scattering data for meaningful biological and physical parameters and comparing the acoustically-inferred to directly measured parameters, thereby allowing the validity of the scattering models to be tested.

The primary objectives of the effort described here are: 1) to understanding and quantifying the contribution to acoustic backscattering from the seasonal pycnocline, 2) to investigate the statistics

Report Documentation Page			Form Approved OMB No. 0704-0188		
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE <b>2010</b>		2. REPORT TYPE		3. DATES COVERED <b>00-00-2010 to 00-00-2010</b>	
4. TITLE AND SUBTITLE <b>Continued Analysis of High-Frequency Broadband Acoustic Scattering from Non-Linear Internal Waves during SW06</b>			5a. CONTRACT NUMBER		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S)			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>Woods Hole Oceanographic Institution, Department of Applied Ocean Physics and Engineering, Bigelow 211, MS #11, Woods Hole, MA, 02543</b>			8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSOR/MONITOR'S ACRONYM(S)		
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)		
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release; distribution unlimited</b>					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT <b>Same as Report (SAR)</b>	18. NUMBER OF PAGES <b>11</b>	19a. NAME OF RESPONSIBLE PERSON
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>			

of the echo envelope for broadband scattering data from microstructure and zooplankton, and 3) to extend the spectral analysis to multiple internal waves.

## APPROACH

Over the last 40 years, there has been significant research effort directed at using high-frequency acoustic scattering techniques to remotely investigate the distribution, abundance, and size of marine organisms (Simmonds and MacLennan, 2005, and references therein). In fact, some of the world's largest stocks of zooplankton, such as Antarctic Krill (Nicol and Endo, 1999), as well as large fish stocks, are assessed using single or multi-frequency narrowband acoustic scattering techniques (Simmonds and MacLennan, 2005). More recently, there has also been significant effort directed towards the quantitative use of narrowband acoustic scattering techniques for investigating small-scale physical processes, such as oceanic microstructure (e.g. Goodman, 1990; Seim et al., 1995; Lavery et al., 2003; Ross and Lueck, 2003; Warren et al., 2003). Acoustic scattering techniques provide a rapid, high-resolution, synoptic, remote sensing alternative to more traditional sampling strategies. Yet reducing the ambiguities in the quantitative interpretation of the acoustic returns, with the ultimate goal of accurate, remote classification and quantification of physical (and/or biological) scattering sources, remains one of the outstanding challenges.

In principle, measurements of high-frequency acoustic scattering from oceanic microstructure and zooplankton across a broad range of frequencies, spanning multiple octaves of bandwidth, can reduce the ambiguities typically associated to the interpretation of acoustic scattering at a single frequency or a limited number of discrete narrowband frequencies. The goal is to capitalize on the different characteristic frequency-dependent spectra associated to different scattering sources. The potential for this technique is supported by broadband measurements on caged aggregations of fish (e.g. Simmonds and Armstrong, 1990; Simmonds *et al.*, 1996), free-swimming individual fish (e.g. Lundgren and Nielsen, 2008), and numerous broadband laboratory measurements of fish (e.g. Reeder *et al.*, 2004; Au and Benoit-Bird, 2008), squid (e.g. Lee *et al.*, 2009), zooplankton (e.g. Roberts and Jaffe, 2008), and different types of microstructure (e.g. Goodman and Oeschger, 2003; Lavery and Ross, 2007), as well as the fact that many toothed whales use broadband echolocation signals to detect and classify their prey (Au *et al.*, 2009).

There are only a few commercially available (Ross and Lawson, 2009: 85–155 kHz, slightly less than octave bandwidth), or custom-built prototype (Foote *et al.*, 2005: 25 kHz to 3.2 MHz using seven octave bandwidth transducers), high-frequency broadband acoustic backscattering systems that have been used for studying zooplankton and/or microstructure in the field. In contrast, lower-frequency broadband scattering measurements ( $< 120$  kHz) to remotely characterize fish have been performed more prevalently (e.g. Zakharia et al., 1996; Stanton *et al.*, 2010), including measurements involving explosives (e.g. Holliday, 1972; Thompson and Love, 1996; Nero *et al.*, 1998; Love *et al.*, 2004).

The broadband system developed for this project was used to measure high-frequency broadband acoustic backscattering from microstructure and zooplankton in the presence of surface trapped nonlinear internal waves of depression propagating over the New Jersey continental shelf. The frequency range used in this study encompasses many of the narrowband acoustic frequencies typically used to survey zooplankton and turbulent oceanic microstructure, and includes the Rayleigh-to-geometric scattering transition of some typical zooplankton and the diffusive roll-off in the

spectrum for scattering from turbulent temperature microstructure for a range of dissipation rates. Almost coincident direct microstructure measurements were performed. Zooplankton community structure was characterized using depth-resolved net-sampling techniques. Some marine organisms, predominantly small fish and zooplankton, can act as passive tracers of physical processes such as internal waves and turbulence, and are a significant confounding factor during the interpretation of high-frequency acoustic volume backscattering. The combination of these data is necessary for the accurate interpretation of the acoustic scattering measurements and, in particular, to determine the relative contribution to scattering from zooplankton and turbulent microstructure. Surface trapped nonlinear internal solitary waves of depression are a unique feature of coastal oceans and provide a good environment to assess the contribution to scattering from oceanic microstructure as they are both intensely turbulent (Moum *et al.*, 2003) and at sufficiently close range that they generate high signal levels well within the range of surface-deployed, high-frequency broadband acoustic scattering systems. Surface trapped nonlinear internal waves of depression are thought to be generated in the vicinity of the continental shelf break due to the interaction of internal tides with stratified fluid over sharp topography. They then propagate across the continental shelf until they dissipate in shallower waters. Not all the internal wave energy is dissipated in shallow waters, as some is dissipated by the generation of turbulence along the propagation path. Mechanisms for this dissipation of energy are discussed by Moum *et al.* (2003). It is hoped that quantification of broadband acoustic scattering from microstructure generated by these internal waves may contribute to understanding these dissipation mechanisms.

The data analysis involves capitalizing on the broadband nature of the transmitted signals and using pulse compression techniques (Chu and Stanton, 1998; Stanton and Chu, 2008) to both increase the signal-to-noise ratio and the spatial resolution of the measurements. It has been possible to obtain almost cm scale resolution in the direction of acoustic propagation using these techniques, a significant improvement over traditional single-frequency echosounder observations of water-column scattering. Additional information is obtained by further capitalizing on the broadband nature of the acoustic signals by using the spectral content of the scattering to determine if the scattering is consistent with scattering from small-scale fluid processes or biology. In regions in which the scattering is determined to be dominated by turbulent microstructure, existing scattering models have been used to extract parameters such as the dissipation rate of turbulent kinetic energy (Lavery *et al.*, 2010).

These measurements are both unique and extensive, and though the results of this project to date have been very promising, only selected portions of the data have been examined in detail, and only the spectrum of the scattering had been fully capitalized on. The research described here extends the analysis of these data to 1) investigate a larger number of internal waves, 2) apply a new “pycnocline” scattering model to the observed enhanced scattering at the pycnocline, and 3) investigating the statistics of the echo returns.

## **WORK COMPLETED**

*Instrument development and calibration:* A 4-channel high-frequency broadband acoustic backscattering system has been developed spanning the frequency range, in four almost overlapping bins, from 150 kHz to 590 kHz with similar acoustic scattering volumes. The system is designed to either profile with the transducers in a side-looking mode or to be suspended at a particular depth with

down-looking transducers (resembling a more traditional echosounder). A SeaBird SBE 49 FastCAT CTD (16 Hz sampling rate) is mounted on the system to measure fine-scale temperature and salinity gradients while in profiling mode. Pitch, roll, and heading are also measured. GPS data are recorded to allow accurate synchronization with other instruments. The system has been calibrated, including measurements of beam patterns, in sea-water tanks at WHOI and at SMAST (on multiple occasions), in the WHOI sea well (also on multiple occasions), and in-situ, using 20 mm and 38.01 mm diameter Tungsten Carbide standard targets

*Field measurements:* This system has been deployed during the SW06/NLIWI experiment during a month long cruise (July 30- August 28, 2006) on the RV Oceanus. Direct microstructure measurements were performed by Jim Moum using the turbulence profiler Chameleon (Moum et al., 1995). The broadband acoustic system was fully operational throughout the experiment and high-frequency broadband acoustic backscattering has been measured for 28 internal solitary wave trains, in some cases chased over many kilometers from generation to dissipation stages. The acoustic system was deployed in both down-looking and side-looking mode, allowing scattering anisotropy during the passage of internal solitary waves to be investigated. In addition, 5 depth-resolved net tows (MOCNESS) were performed during this experiment in order to quantify biological scatterers.

*Analysis of microstructure and biological measurements:* Jim Moum is primarily responsible for the analysis of the microstructure measurements, and much of the data collected during the field experiment has been analyzed. These data have been used with existing scattering models (Lavery et al., 2003) to predict scattering from microstructure, and to assess the importance of salinity versus temperature microstructure. These data helped guide the locations for which intensive acoustic analysis was performed. The shelf-break MOCNESS tows (2-5) have been analyzed for composition, size, and abundance of zooplankton. Predictions of scattering from zooplankton based on existing scattering models (Lavery et al., 2007) have been performed for these tows (the “forward problem”) to determine the contribution to scattering from biology and to determine the dominant biological scatterers (Lavery et al., 2010).

*Spectral analysis of acoustic scattering data:* The spectral analysis of the broadband acoustic scattering data has focused on locations at which particularly strong temperature gradients and high dissipation rates were observed, such as Kelvin-Helmholtz shear instabilities (Moum et al., 2003). Elevated scattering from microstructure relative to zooplankton is expected at these locations. Two manuscripts have resulted from this recent work (Lavery et al., 2010).

*Turbulence anisotropy:* Doris Leong, a recently graduated M.Sc. student at Dalhousie University has used the broadband acoustic scattering spectra measured during the SW06/NLIWI experiment to assess the importance of turbulence anisotropy (Leong, 2009; Leong et al., submitted).

*Pycnocline scattering model (current research):* Elevated scattering at the depth of the pycnocline was often observed, even before the arrival of the NLIWs. The measured scattering spectra for the pycnocline typically show little frequency dependence, or were very slightly decreasing with increasing frequency. The mechanism giving rise to this scattering layer has not yet been unambiguously identified: It may arise from 1) larger zooplankton alone, in which the Rayleigh-to-geometric scattering transition has already occurred, 2) a “mixed” scattering mechanism, in which the contribution at lower frequencies is dominated by turbulent temperature microstructure or large

zooplankton while the contribution at higher frequencies is dominated by small zooplankton, or 3) coherent scattering (reflection) from the pycnocline, that is, scattering from strong temperature and salinity gradients. Though it is difficult to distinguish between these different mechanisms, a physics-based, gradient scattering model, that incorporates measured density and sound speed gradients, has been developed (Ross and Lavery in preparation, modified from Lavery and Ross, 2007) and predictions at select sites have been compared to the measured pycnocline scattering to help elucidate the possible scattering mechanisms. The coincident high-resolution profiles measured directly with the microstructure profiler have been used as input for the scattering model. This simple model consists of dividing the density and sound speed profiles into a finite number of sublayers, each with homogeneous density and sound speed. The upper and lower mixed layers are modeled as homogeneous half-spaces. The scattered pressure at each interface is then calculated and added coherently. The scattering from the pycnocline falls into the weak-scattering regime as the density and sound speed gradients, based on measurements of temperature and salinity, were small.

*Echo statistics (current research):* The echo statistics of scattering from fish are relatively well studied (e.g. Stanton, 1985; Stanton and Clay, 1986; Stanton et al., 2004; Chu and Stanton, 2010; Stanton and Chu, 2010) and have been shown to produce, for example, estimates of fish densities. The echo statistics of scattering from zooplankton are less well studied (e.g. Stanton, 1985; Stanton et al., 2004; Trevorror and Tanaka, 1997; Trevorror et al., 2005), though these too have resulted in estimates of zooplankton abundance (Stanton et al., 2004; Trevorror and Tanaka, 1997; Trevorror et al., 2005). The published studies on the echo statistics of zooplankton have focused on either relatively large individuals, such as euphausiids or amphipods (Stanton, 1985; Stanton et al., 2004; Trevorror and Tanaka, 1997), and/or relatively rare and strong scatterers, such as siphonophores (Trevorror et al., 2005). The current analysis focuses on echoes from relatively small zooplankton, such as pteropods or copepods, potentially in the presence of microstructure or in mixed zooplankton assemblages. In addition, the echo statistics of backscattering from turbulent oceanic microstructure has received virtually no attention, even though the echo statistics of acoustic scattering from a turbulent atmosphere has been better studied (Kallistratova, 2002). For scattering from homogeneous and isotropic turbulent oceanic microstructure, it is expected that the probability density function (PDF) will be generally Rayleigh-like. Similarly, it is expected that the PDF for a patch of unresolved small zooplankton will be generally Rayleigh-like. However, by looking carefully at the echo PDFs, it is possible to determine the density of any resolved larger individuals within a patch of unresolved zooplankton or turbulence, for example occasional fish or large zooplankton (e.g. euphausiids) present in a patch of smaller zooplankton (Stanton, 1985), with implications to predator-prey relationships. This also has implications for determining the possible contribution from larger zooplankton to scattering observed at the pycnocline.

## RESULTS

*High-resolution imaging of small-scale physical processes:* Broadband acoustic scattering measurements enable the use of pulse compression signal processing techniques to obtain very high resolution images of many nonlinear internal waves. In combination with the high ping rate (1 Hz), these techniques have allowed fine scale physical processes, such as Kelvin-Helmholtz shear instabilities, typically not well resolved by the direct microstructure measurements, to be imaged at very high resolution (Lavery et al., 2010). Though the direct microstructure measurements provide

very high resolution measurements in the vertical, the profiles are relatively sparse (one profile every 2-4 minutes) relative to the acoustic measurements or the spatial scales of the KH instabilities.

*Analysis of biological samples and the forward problem based on these data:* All the MOCENSS tows performed on the continental shelf during the SW06 experiment have been analyzed (MOCs 2-5). The results show that, in general, biomass and numerical abundance of zooplankton are dominated by copepods, with larger copepods located in a deep scattering layer and the shallower waters being populated by smaller copepods. All tows were performed during day light hours. Scattering predictions based on these data and available zooplankton models (Lavery et al., 2007) have shown that the predicted scattering from zooplankton is dominated by copepods, amphipods, and pteropods, depending on the frequency, depth, and location (Lavery et al., 2010).

*Forward problem based on microstructure data:* Scattering predictions have also been made based on the microstructure data and turbulent microstructure scattering models, at select locations. These predictions suggest that the scattering from microstructure is dominated by temperature and not salinity microstructure, as would be expected based on the temperature and salinity gradients (Lavery et al., 2010).

*Scattering due to small-scale physical processes versus biology:* Though the frequency response of the scattering was often consistent with scattering from small zooplankton (scattering increasing with increasing frequency), some regions have been found in which the scattered frequency spectra are indicative of scattering from physical processes (Lavery et al., 2010). Specifically, scattering spectra from Kelvin-Helmholtz shear instabilities were frequently consistent with scattering from microstructure alone (scattering decreases with increasing frequency).

*Inversion of broadband data for biological and physical parameters:* Simple least squares inversions of the broadband scattering data have been performed at locations in which the scattering spectra are consistent with scattering from small zooplankton alone, and consistent with scattering from microstructure alone. These inversions rely heavily on existing scattering models. For zooplankton, a single scattering type is assumed and the inversions result in size and abundance of that type of scatterer. For microstructure, the inversions allow the dissipation rate of turbulent kinetic energy and temperature variance to be deduced (Lavery et al., 2010). For both these types of inversions the results are consistent with the direct sampling techniques, though high noise levels on the two highest frequency channels only allowed high values of dissipation rates of turbulent kinetic energy to be inferred. However, these results strongly suggest that the existing scattering models for homogeneous and isotropic turbulence are adequate to describe the scattering.

*Scattering anisotropy:* By comparing broadband acoustic scattering spectra measured in horizontal and vertical mode, it has been possible to assess the importance of anisotropy on scattering. The overall scattering shows statistical patterns in spectral shape that suggests anisotropy occurs in either the biology or microstructure, though there was insufficient bandwidth and/or groundtruthing to determine which. However, turbulence dissipation rates inferred from acoustic inversions of spectra yield no clear evidence of small-scale turbulence anisotropy (Leong, 2009; Leong et al., submitted).

*Scattering from the seasonal pycnocline (current research):* The pycnocline scattering model has been applied to a number of oceanic pycnoclines (Ross and Lavery, in prep), based on measured

temperature and salinity profiles. However, though there are a number of locations in which high-frequency acoustic backscattering from oceanic pycnoclines is predicted to be measurable, particularly locations in which there is significant salinity gradient, the predicted scattering from the seasonal pycnocline during SW06 was not able to account for the observed scattering. It is possible that turbulence or passive tracers were contributing significantly to the scattering, though a location was chosen in which the turbulence levels measured directly were not significant, and thus turbulence was not predicted to dominate the scattering. This analysis is still being extended to other locations during the SW06 experiment.

*Echo statistics (current research):* The statistics of the echo envelope after pulse compression for broadband scattering data from microstructure and zooplankton collected during the passage of non-linear internal waves during the SW06 have been investigated. Sequential pings within areas that are spectrally classified as due to turbulence alone, zooplankton alone, due to a mixture of the two, and due to noise have been investigated. In all cases the probability density function (PDF) was generally Rayleigh-like. However, in the upper mixed layer, for which there was not sufficient spectral structure (flat to slightly decreasing scattering spectrum) or ground-truthing information for the scattering mechanism to be definitively identified, the measured PDF was mildly non-Rayleigh. This supports the hypothesis that the scattering in the upper mixed layer might be due, at least in part, to larger scatterers, such as fish or larger zooplankton that have already reached the Rayleigh to geometric scattering transition.

*Future research goals for SW06 data analysis:* One of the remaining goals on this project is to extend the data analysis approaches taken so far at select locations, including the spectral analysis, scattering from the pycnocline, and the echo statistics, and apply them to more internal waves spanning a larger range of environmental conditions encountered during SW06.

## **IMPACT/APPLICATIONS**

It is important to understand the circumstance under which different processes and/or targets contribute to high-frequency acoustic scattering. For example, a common misconception is that high-frequency acoustic scattering in the water-column is dominated by biological organisms. Only recently has it become more accepted that microstructure can also contribute to scattering, under certain circumstances. Similarly there is only anecdotal evidence that the seasonal pycnocline can contribute to high-frequency acoustic backscattering. The results of the measurements performed here provide additional evidence that small-scale turbulent fluid processes can be significant contributors to volume scattering in regions of internal solitary waves. This project has also developed high-frequency broadband acoustic scattering techniques that 1) increase the circumstances under which scattering from microstructure and biology can be distinguished, and 2) increase the spatial resolution with which physical and biological processes are imaged, which is especially relevant as it has become increasingly evident that thin biological and physical layers are prevalent in coastal regions.

## **RELATED PROJECTS**

“Development of an autonomous broadband acoustic scattering system for remote characterization of zooplankton (Part II),” Lavery A.C. Funded by ONR Marine Mammals and Biology.

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## **HONORS/AWARDS/PRIZES**

Andone C. Lavery was awarded a WHOI Coastal Ocean Institute Fellowship from 2006-2009.